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Medium-Access Control Protocols for Heterogeneous Mobile Ad Hoc Networks with Directional Antennas

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NATO Workshop on Cross-Layer Issues in the Design of Tactical Mobile Ad Hoc Wireless Networks

June 2, 2004

(This work was supported in part by the DOD Multidisciplinary University Research Initiative (MURI) program administered by the Office of Naval Research under grant N00014-00-1-0565 and in part by the U.S. Army Research Laboratory and the U.S. Army Research Office under grant DAAD19-00-1-0156.)

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 DEC 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED
4. TITLE AND SUBTITLE **Cross-Layer Issues In The Design Of Tactical Mobile Ad HOC Wireless Networks: Medium-Access Control Protocols for Heterogeneous Mobile Ad Hoc Networks with Directional Antennas**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Clemson University**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**12**	

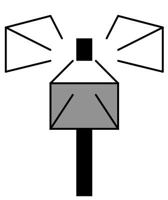
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Directional Antennas in Mobile Ad Hoc Networks

- Great performance benefits if directional antennas utilized effectively in mobile ad hoc networks

- Directional antennas can result in high complexity
  - Adaptive beam-forming, management of beam pointing
  - Complex neighbor discovery, need for location information

- Our focus: fixed-beam antenna subsystems exploited with relatively simple protocols/algorithms
  - Multiple fixed-beam directional antennas at node
    - together give node **omni-directional coverage** in azimuth
    - **separate transceiver** for each beam
    - number of beams may differ for different nodes

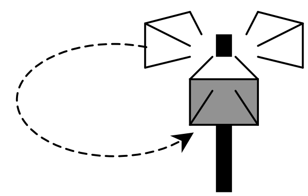


- Characteristics of node with multiple fixed beams/transceivers
  - Cost is multiple transceivers rather than signal processing
  - No management of beam-pointing by protocols required
  - No beam switching at transceiver front end is required
  - Neighbor discovery same as with omni-directional antennas
  - No explicit location information required

- Necessary/desirable properties of MAC protocol
  - MAC management of transceivers is consistent with physical-layer constraints of antenna subsystems
  - MAC mitigates unique performance limitations arising due to physical-layer characteristics of antenna subsystems
  - Same MAC supports nodes with any number of beams

Relationship Between Physical-Layer Characteristics and MAC-Layer Design

- Multiple antenna subsystems at node result in **co-site interference** among transceivers



  - Signal energy from one transceiver coupled into another transceiver through antennas, other EMI mechanisms
  - Possible MAC-layer solutions:
    - no TX at node when RX expected by any transceiver at node
    - TX limited only based on characteristics of antenna subsystems

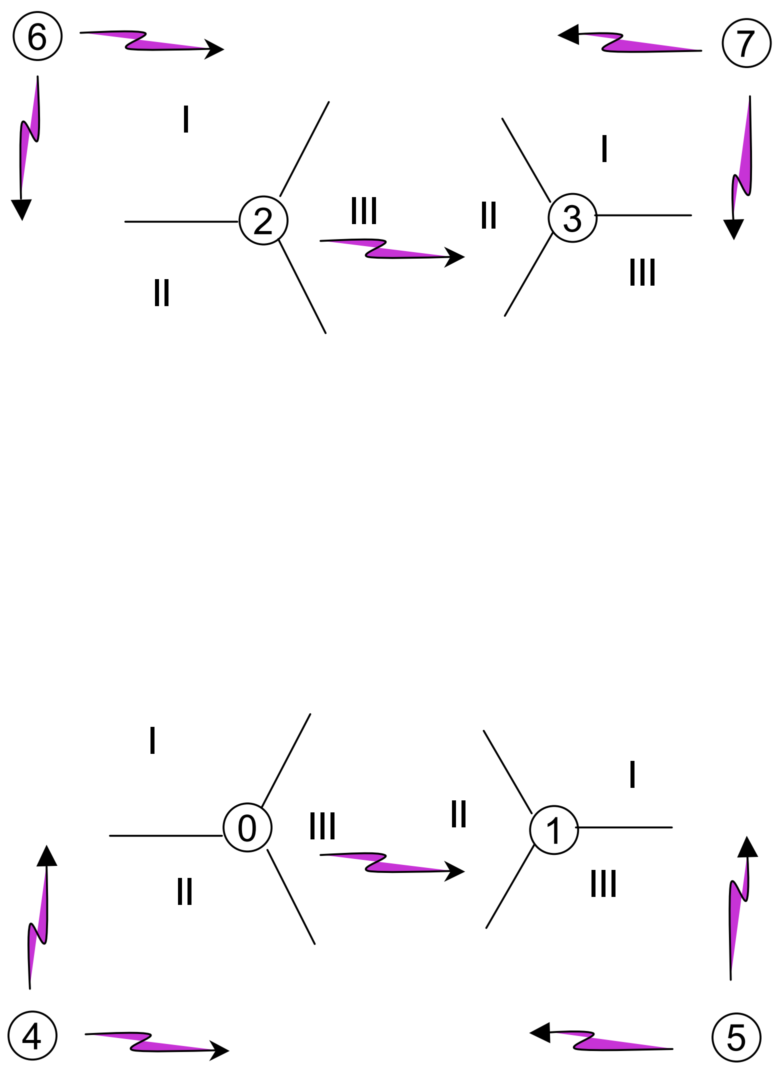
- Use of directional antennas exacerbates the **receiver blocking problem** in packet radio network
  - MAC-layer solution must address this problem for best performance

System Design

- Characteristics of nodes in network
  - Node with omni-directional antenna has one half-duplex transceiver
  - Node with multiple beams has one half-duplex transceiver per beam
  - Collision-avoidance (RTS-CTS) random-access MAC protocol
  - Direct-sequence spread-spectrum packet transmission

- "Baseline" MAC protocol addresses co-site interference problem
  - Multiple frequency channels:
    - One control channel for RTS, CTS packets
    - One or more traffic channels for DATA, ACK packets
  - Intercepted CTS blocks local use of a frequency channel in beam (mitigates hidden-terminal problem)
  - Exponential back-off algorithm (response to perceived busy terminal)
  - Single MAC layer controls transceivers of all beams at a node
  - Expected packet reception at any beam's transceiver blocks all transmissions at node

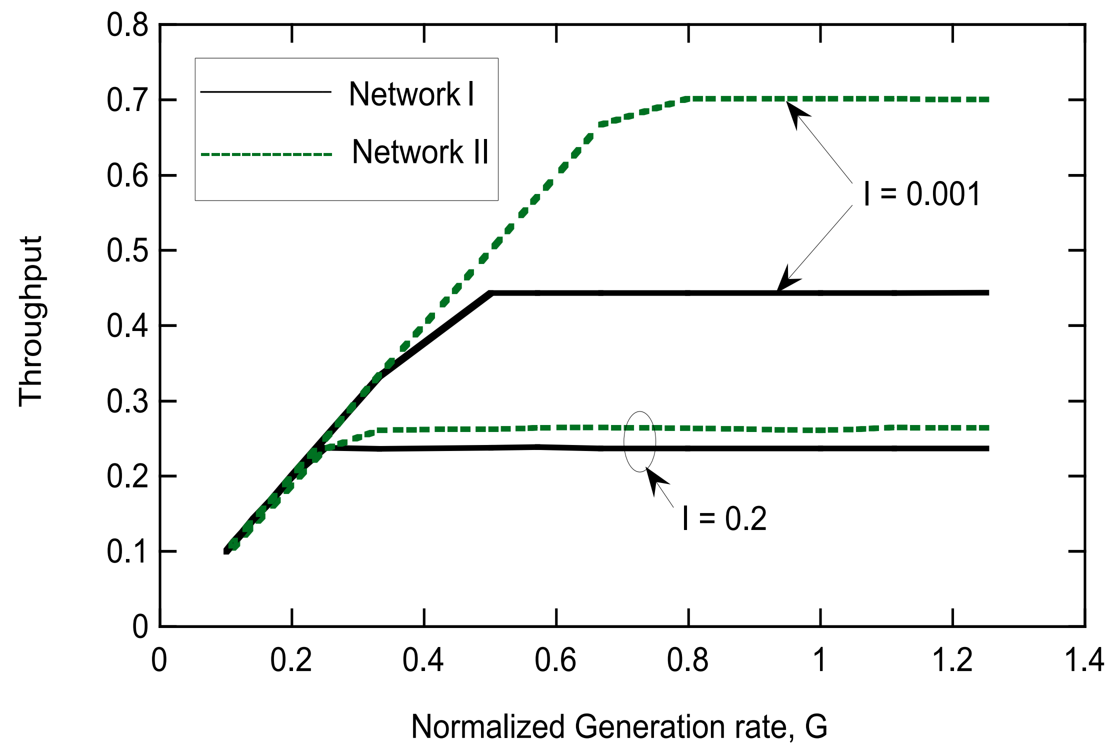
Example of Eight-Node Network



- Two frequency channels
- Two scenarios considered
  - Network I: All nodes have omni-directional antennas
  - Network II: Nodes 0-3 have three 120-degree beams each
- Beam orientation in network II isolates active 0-1 link from active 2-3 link
- Poisson traffic at each node
  - Node 0 to node 1: rate G
  - Node 2 to node 3: rate G
  - Nodes 4-7 to adjacent corners: rate I/2
- Performance measure
  - Link-layer throughput, no routing
  - Throughput per node for 0 and 2

Performance with Baseline MAC Protocol

- Directional antennas reduce MAI on links of interest
- With no interfering traffic, expect doubling of throughput with directional antennas
  - Anticipated doubling is observed
- With heavy interfering traffic, expect greater benefit from directional antennas
  - **Opposite** phenomenon is observed



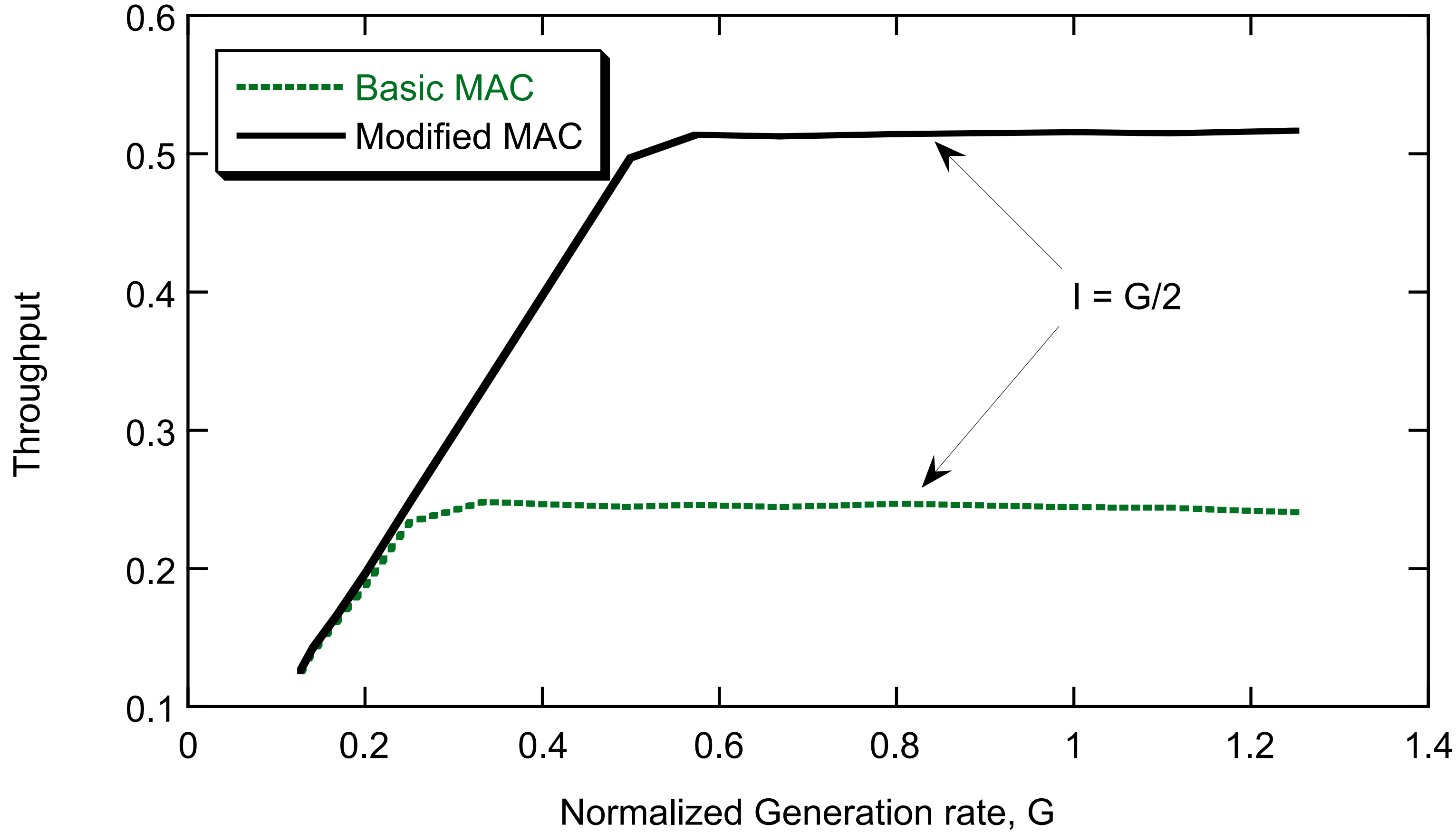
Performance with Baseline MAC Protocol

- Throughput more sensitive to interfering traffic if nodes 0-3 employ directional antennas
  - Introduction of directional antennas actually *decreases* throughput in this network if interfering traffic is heavy
- Phenomenon is a manifestion of the **receiver blocking problem**
  - Transmitter of RTS erroneously infers “busy radio” from missing CTS, initiates back-off algorithm
  - Problem also arises with omni-directional antennas
  - Random placement of interferer more likely to cause problem for node with directional antenna than with omni antenna
  - So problem has greater impact on performance if some nodes employ directional antennas

A Simple Solution: the negative CTS

- A node with all local traffic channels blocked for a beam can still transmit on control channel
- Transmitter can be more aggressive in retransmission attempts if intended receiver has blocked channels than if it is busy
- Modified MAC protocol
  - Transmitter still employs original back-off algorithm in response to missing CTS
  - Receiver with all traffic channels blocked responses to RTS with negative CTS (NCTS) containing information about channel availability
  - Transmitter exploits NCTS information to determine aggressiveness of retransmission algorithm
    - Algorithm accounts for information in recent NCTS packets
- Modified MAC protocol improves performance with both directional antennas and omni-directional antennas
  - Greater improvement occurs for network employing some nodes with multiple directional antennas

Performance with Modified MAC Protocol



More than two-fold increase in throughput under heavy-traffic conditions

Conclusions

- Properly designed MAC protocol mitigates co-site interference at node with multiple fixed-beam antennas
- Packet radio network including nodes with directional antennas is more vulnerable to receiver-blocking problem than network with only omni-directional antennas
- Alternative collision-avoidance MAC protocol mitigates receiver blocking by using negative CTS control packet
  - Improves performance of network with only omni antennas
  - Provides greater improvement if some nodes have directional antennas

Reference

A. Swaminathan, D. L. Noneaker, and H. B. Russell, “The Receiver Blocking Problem in a DS Mobile Ad Hoc Network with Directional Antennas,” to appear in the *Proceedings of the 2004 IEEE Military Communications Conference* (Monterey, CA), Nov. 2004.